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Composite Structures 75 (2006) 60–66

COMPOSITE STRUCTURES

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2-D biaxial testing and failure predictions of IM7/977-2 carbon/epoxy quasi-isotropic laminates ☆

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Abstract

In previous research, a series of a thickness-tapered cruciform specimen configurations have been used to determine the biaxial (two-dimensional, in-plane) and triaxial (three-dimensional) strength of several carbon/epoxy and glass/vinyl-ester laminate configurations. Refinements to the cruciform geometry have been shown capable of producing acceptable results for cross-ply laminate configurations. However, the presence of a biaxial strengthening effect in quasi-isotropic, $[(0_N/90_N/\pm 45_N)_M]_S$, laminates have brought into question whether the cruciform geometry could be used to successfully generate two-dimensional strength envelopes. In the present study, a two-dimensional failure envelope for a IM7/977-2 carbon/epoxy laminate was developed at the Air Force Research Laboratory, Space Vehicles Directorate, using a triaxial test facility. The electromechanical test frame is capable of generating any combination of tensile or compressive stresses in σ_1:σ_2:σ_3 stress space and can evaluate the uniaxial (one-dimensional, in-plane), biaxial or triaxial response of composite materials. Results are promising as they indicated that failure in the majority of the IM7/977-2 specimens occurred in the gage section. This leads the authors to believe that maximum biaxial stress states were correctly generated within the test specimen. In addition to the experimental data presented, multi-continuum theory (MCT) was used to predict and analyze the onset of damage and ultimate failure of a biaxially loaded IM7/977-2 laminate. Multi-continuum theory is a micromechanics based theory and associated numerical algorithm for extracting, virtually without a time penalty, the stress and strain fields for a composites' constituents during a routine structural finite element analysis. Damage in a composite material typically begins at the constituent level and may, in fact, be limited to only one constituent in some situations. An accurate prediction of constituent failure at sampling points throughout the laminate provides a genesis for progressively analyzing damage propagation in a composite specimen allowing identification of intermediate damage modes. A constituent-based, quadratic, stress-interactive, failure criterion was used to take advantage of the micro-scale information provided by MCT. There was reasonable correlation between analytically and experimentally developed IM7/977-2 2D failure envelope which leads us to believe that the thickness-tapered cruciform specimen can be used to determine the biaxial strength of quasi-isotropic laminates.

Keywords: Biaxial testing; Multi-axial testing; Composites testing; Composite failure predictions

1. Background

One of the requirements of a design engineer is to have the capability to accurately simulate failure of a composite structure. The term "accurately" is defined in a laboratory when good correlation is achieved between analytical and experimental results. Thus, the ability to experimentally generate precise biaxial stress states is of paramount importance. The laminated architecture of advanced fiber reinforced composite structures generates complex three-dimensional stress states even under simple uniaxial loading. As has been demonstrated repeatedly in the literature, conventional analysis techniques have difficulty accurately predicting these stress states. Most recently, the completion of the World-Wide Failure Exercise (WWFE) [1] exposed

☆ Thirteenth International Conference on Composite Structures, Monash University.

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doi:10.1016/j.compstruct.2006.04.049

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **2-D biaxial testing and failure predictions of IM7/977-2 carbon/epoxy quasi-isotropic laminates**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **CSA Engineering Inc,1451 Innovation Parkway SE,Albuquerque,NM,87123**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

the lack of a single unified failure theory within the composite community that can accurately predict the initial onset and final failure of a general laminate under general loading. Almost all of the 19 failure theories tested worked well in some and poorly in remainder of the fourteen test cases: four different fiber/matrix combinations, six different laminate stacking sequences and approximately six different (uniaxial and biaxial) loading conditions. The WWFE also exposed the paucity of reliable experimental data for biaxally (2-D) and triaxially (3-D) loaded composite materials. While more advanced failure analysis techniques are continuously being developed, very little has been done to address the lack of reliable experimental data. Previous techniques have been limited in their ability to overcome specimen buckling, both at the macro (structural) and micro (fiber) scales, when loaded in the compression/compression regime (quadrant III in 2-D stress space) and biaxial strengthening in the tension/tension regime (quadrant I). Biaxial strengthening refers to the prediction by stress-interactive failure criteria, e.g. Tsai-Wu, that the 2-D failure envelope will be an ellipse (an ellipsoid failure surface in 3-D) with the major axis +45° to the abscissa and a zero ordinate intercept, i.e., occupying quadrants I and III in σ_1–σ_2 stress space when plotted in rectangular coordinates. The composites community has clearly and repeatedly demonstrated the need for reliable experimental biaxial data [1–4].

Although the Air Force Research Laboratory (AFRL) has an operational triaxial test facility dedicated to the evaluation of composite materials, a quasi-isotropic laminate configuration had never been successfully tested. Additionally, results from the WWFE indicate that this widely used laminate configuration may exhibit strong biaxial strengthening effects that have not been thoroughly verified experimentally. Thus, the objective of this research was to evaluate the performance of quasi-isotropic, $[(0_N/90_N/\pm 45_N)_M]_S$, graphite/epoxy, IM7/977-2, composite laminate when subjected to applied biaxial loads. A representative series of 2-D load ratios were explored to quantify the effect of biaxial loading on stiffness and strength.

2. Experimental procedures

The experimental portion of the present study began by defining a successful biaxial test to be one in which specimen failure, at maximum load, must occur in or around the specimen's gage section. Biaxial strengthening effects can make this a difficult objective to obtain for certain laminate architectures in general and a quasi-isotropic one in particular. Using biaxial cruciform specimens, Fig. 1, it is therefore reasonable to expect unacceptable failures to occur in the arms (which are loaded uniaxially) rather than in the biaxially loaded, hence strengthened, gage section. In previous research [3,4] cross-ply laminates have been successfully tested, in part, due to their low in-plane Poisson's response (off-axis terms in the stiffness matrix, which account for internally generated multiaxial stress states, are a function of Poisson's ratios). Furthermore, the experience gathered

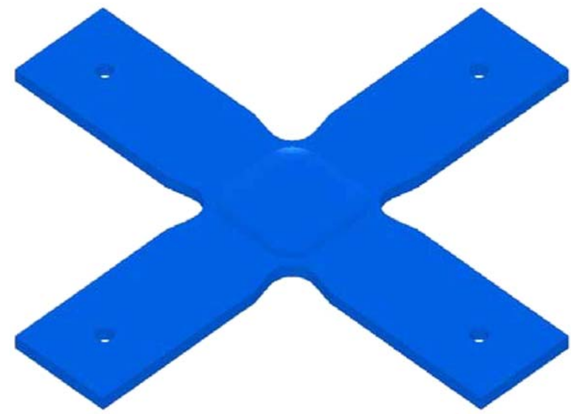

Fig. 1. Thickness-tapered cruciform specimen.

by the current authors led them to believe that a fiber reinforced quasi-isotropic laminate (which exhibit a larger in-plane Poisson's response) could be successfully tested provided appropriate specimen geometry and sufficient reinforcement was placed in the loading arms.

Although various cruciform configurations have been studied [4], the focus of this program was to fabricate and test a quasi-isotropic laminate. Existing failure theories indicate that a quasi-isotropic laminate would be significantly (2×) stronger when loaded biaxially than when loaded uniaxially. Experimentally this increases the probability of premature failure in the uniaxially loaded arms resulting in an invalid test. To prevent this, a quasi-isotropic laminate was designed with integrated cross-ply tabs on the arms using a $[(0/90)_4(0/45/-45/90)_2]$s laminate configuration. The thickness-tapered cruciform specimens were initially laid-up as flat laminate plates from which the desired cruciform specimen shape, including gage section, was machined out using a computer numeric controlled (CNC) mill and high-speed router. That is, in physically machining the specimen to the desired thickness, the (0/90) portions of the laminate was removed from the gage section but retained in the loading arms. Material remaining in the gage section was the desired (0/45/−45/90) quasi-isotropic laminate to be tested. A total of 52 thickness-cruciform specimens were fabricated for testing in twelve different biaxial stress ratios, three repetitions each, to determine the strengths in each of the four quadrants in σ_1–σ_2 stress space. Approximately 1/3 of the test specimens were instrumented with either uniaxial or biaxial strain gages to monitor the strain to failure.

The biaxial tests were performed utilizing the triaxial testing facility shown in Fig. 2. This electromechanical test facility was developed specifically to evaluate the biaxial (two-dimensional, in-plane) and triaxial (three-dimensional) response of composite materials. This experimental test facility is capable of generating any combination of tensile or compressive stresses in σ_1–σ_2–σ_3 stress space [3,4].

Because cruciform-shaped specimens have two intersecting loading directions, there exists the possibility of load transfer between adjacent loading arms. That is, a portion of the load applied by one arm in one direction may be

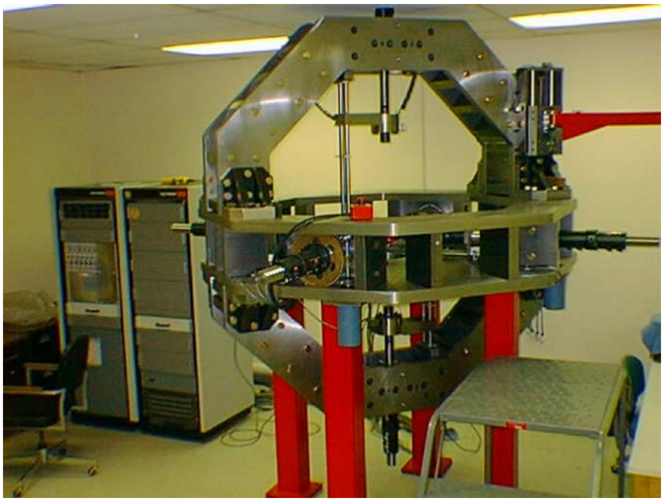

Fig. 2. Triaxial test facility.

reacted by another loading arm bypassing the gage section and leading to inaccurate assumptions of biaxial stress levels in the gage section. Fortunately, it is possible, but not trivial, to quantify the levels of load sharing for each material system and specimen geometry. Referred to as the *bypass correction factor* (BCF), this value gives an indication of the amount of applied force that bypasses the thickness-tapered gage section [3,4].

Since this study represented one of the first efforts involving quasi-isotropic laminates, considerable effort was expended to determine the exact value of the bypass ratio for each specimen tested. The process began by mounting a single uniaxial strain gage placed in the center of the gage section. Using this gage, the actual stress level in the gage section of a thickness-tapered cruciform specimen was obtained by multiplying the measured strain by the effective modulus of elasticity of the laminate (developed via classical lamination theory [5]) being tested. To minimize extraneous variables during this procedure, the cruciform specimen was loaded uniaxial, i.e., only one pair of opposing arms was loaded. The stress results generated using this configuration were then simultaneously compared to stress values obtained by dividing the applied force (average value of both opposing load cells) measured along a loading axis by the cross-sectional area of the thickness-tapered cruciform specimen gage section. A comparison of these two stress values quantifies the BCF as the amount of load that is bypassing the gage section of the cruciform specimen. That is, the bypass correction factor is determined by

$$\mathrm{BCF} = \frac{(\mathrm{Modulus})_{\mathrm{effective}}(\varepsilon)_{\mathrm{measured}}}{(\mathrm{Load})_{\mathrm{measured}}/(\mathrm{Area})_{\mathrm{measured}}}.$$

Any geometric modifications to the thickness-tapered cruciform specimen will require a new BCF. The motivation behind quantifying the BCF in terms of stress levels is that to eliminate the need for strain instrumentation on every specimen. The specific BCFs used for the present study were 0.86 and 0.79–0.87 for tensile and compressive loadings, respectively.

Once each thickness-tapered cruciform specimen was machined, the procedure for generating ultimate biaxial strength values began by loading each cruciform specimen into the triaxial testing facility shown in Fig. 2 in accordance with established practices [3,4]. Each specimen was loaded at a rate of 1.27 mm/min while maintaining the appropriate stress ratio until ultimate specimen failure occurred. The stress ratio was performed in load control by maintaining a constant ratio of applied stress in the global x-direction (drive axis) to the applied stress in the global y-direction (slave axis). The notation,

$$\text{stress ratio} = (\mathrm{Load})_x/(\mathrm{Load})_y,$$

is used to identify a particular stress ratio, with a positive sign indicating tensile and a negative sign indicating compressive values. For example, a stress ratio of $1/-2$ denotes a test in which the magnitude of the compressive stress applied in the y-direction is twice that of the tensile stress applied in the x-direction. The stress ratios performed in the present study for the quasi-isotropic laminate were 1/1, 2/1, 3/1, 1/0, $2/-1$, $3/-1$, $1/-1$, $1/-2$, $-1/0$, $-1/-2$, $-2/-3$ and $-1/-1$. Finally, the measured biaxial strength of each specimen was corrected using the associated BCF. A BCF has been applied to all experimental data presented in this paper.

3. Numerical procedures

Structural damage of a composite material begins at the level of its constituents and may, in fact, be limited to only one constituent in some situations. Conventional analysis using blending methodology, e.g., blending fiber and matrix material properties to develop effective lamina (composite) properties, loses the ability to examine constituent level behavior where damage initiates. This makes it analytically difficult to accurately predict pre-, ongoing, and post-damage conditions of the laminate. Conversely, the ability to accurately predict constituent damage throughout a laminate allows for a high resolution failure analysis of any composite structure from the initiation of damage to ultimate rupture, promoting more efficient remedies to improve the design. Multicontinuum theory (MCT) [6,7] incorporates the classical micromechanics based strain-decomposition technique of Hill [8] into a numerical algorithm that extracts the stress and strain fields for a composites' constituents. Thus, MCT retains the basic nature of the composite's constituents (fiber and matrix) in a structural analysis as separate but linked continua so that the responses of these most basic components can be determined at every point in the structure. MCT does this in an efficient manner that result in a high resolution window on the behavior of a composite structure at its most basic level, i.e., the individual constituents. Constituent stress- or strain-based failure criterion can then be used to construct a nonlinear progressive failure algorithm for investigating the material failure strengths of composite laminates. MCT has been incorporated into a proprietary finite element code [9,10] as well as user-defined subroutines in commercial codes such as ANSYS™ and ABAQUS™.

Failure criteria can be broadly classified as either interactive or non-interactive in the field variable of interest which is typically stress or strain. Maximum stress is a well accepted example of non-interactive failure criteria. It states that failure will occur in a material under a general multiaxial load when the magnitude of any component of the stress tensor reaches the value determined experimentally in a uniaxial test to rupture. Mathematically the maximum stress is expressed as

$$\frac{\sigma_{ij}}{\sigma_{ij\,\max}} \geqslant 1 \quad \text{or} \quad \frac{\varepsilon_{ij}}{\varepsilon_{ij\,\max}} \geqslant 1,$$

where σ_{ij} and ε_{ij} are the components of the stress and strain tensor respectively. The 2-D stress-space failure envelope generated by the Maximum stress criteria for a σ_{11}:σ_{22} biaxial load is shown in Fig. 3.

When the maximum stress criteria is transposed into strain-space via the constitutive relations

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \varepsilon_{12} \\ \varepsilon_{13} \\ \varepsilon_{23} \end{Bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} & s_{14} & s_{15} & s_{16} \\ & s_{22} & s_{23} & s_{24} & s_{25} & s_{26} \\ & & s_{33} & s_{34} & s_{35} & s_{36} \\ & & & s_{44} & s_{45} & s_{46} \\ & \text{SYM} & & & s_{55} & s_{56} \\ & & & & & s_{66} \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{Bmatrix},$$

it becomes an interactive criteria by virtue of the off-diagonal terms of the compliance matrix [S]. The maximum stress criteria, also known as St. Venant's criterion, is shown in Fig. 4.

Fig. 4 clearly shows that in the tension–tension (quadrant I) and compression–compression (quadrant III) loading regimes the material is capable of attaining stress values

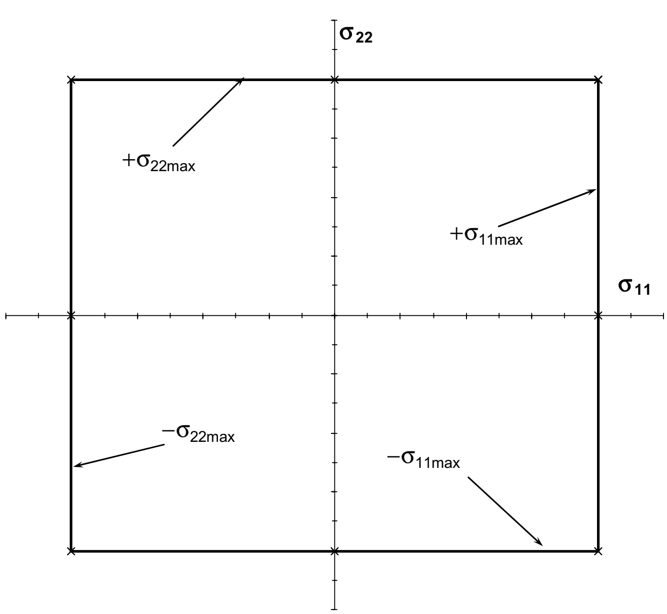

Fig. 3. Maximum stress 2-D failure envelope in stress space.

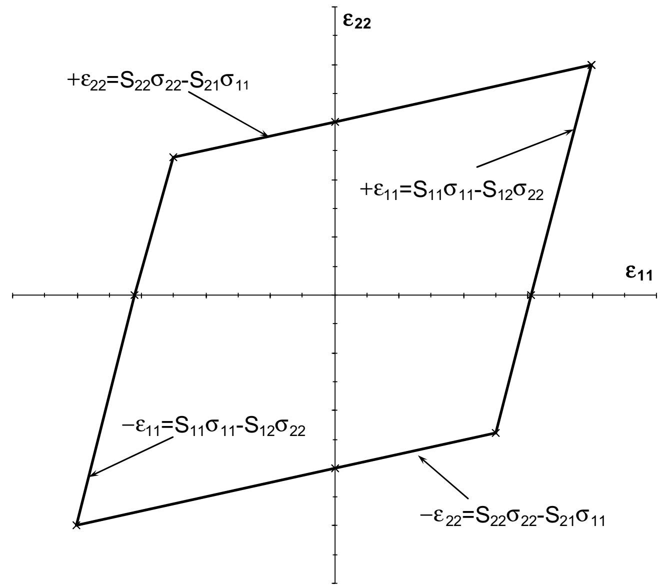

Fig. 4. Maximum stress 2-D failure envelope in strain space.

significantly higher than the uniaxial (axis intercept) values. Other widely accepted interactive failure criteria that indicate strengthening in quadrants I and III are the maximum distortion energy theory, also know as the von Mises criteria extended to orthotropic materials by Hill [11], and the Tsai-Wu criteria [12].

MCT uses a constituent-based, quadratic, stress-interactive, failure criterion originally proposed by Hashin [13] and modified by Mayes [14] to predict and analyze the onset of damage and ultimate failure of a biaxially loaded IM7/977-2 laminate. Hashin identified two composite failure modes; fiber versus matrix influenced, and developed separate equations based on the failure mode to determine a failure state. Hashin further recognized that a composite typically has different ultimate strengths in tension and compression, so both fiber and matrix failure criteria have tensile and compressive subforms. Hence the coefficients of the stress terms are functions of only tension or compression strengths resulting in a piecewise continuous stress-space failure surface.

Mayes adopted the view of Hashin and recognized separate failure criteria for the fiber and matrix failure modes. However, in a major departure from Hashin's work, a failure criteria was developed for *each constituent* as opposed to the composite by utilizing constituent stress information produced by MCT. Furthermore, recognizing that constituents typically have different ultimate strengths in tension and compression, each constituent failure criterion has a tensile and compressive subform. The general form of the failure criteria is

$$K_1 I_1^2 + K_2 I_2^2 + K_3 I_3 + K_4 I_4 = 1,$$

where the coefficients of the stress terms, K_i, are determined empirically from a suite of six ASTM standard material tests conducted for the most part on unidirectional laminates. I_j are the transversely isotropic stress invariants

$$
\begin{aligned}
I_1 &= \sigma_{11},\\
I_2 &= \sigma_{22} + \sigma_{33},\\
I_3 &= \sigma_{22}^2 + \sigma_{33}^2 + 2\sigma_{23}^2,\\
I_4 &= \sigma_{12}^2 + \sigma_{13}^2,\\
I_5 &= \sigma_{22}\sigma_{12}^2 + \sigma_{33}\sigma_{13}^2 + 2\sigma_{12}\sigma_{13}\sigma_{23}
\end{aligned}
$$

determined for each constituent of the composite material under consideration.

A single finite element was used to simulate the far-field three-dimensional stress state in the IM7/977-2 laminate under biaxial load and generate two-dimensional failure envelopes.

4. Results and discussion

Fig. 5 presents experimentally and analytically generated biaxial failure envelope for the quasi-isotropic IM7/977-2 laminates tested.

Both the experimental and analytical data assume symmetry of the load and laminate which creates a line of symmetry in the figure +45° to the abscissa with a zero ordinate intercept. Only one half of the data points shown in Fig. 5 were actually determined (lower half of quadrants I and III, all of quadrant IV) with the remaining points being a mirror reflection across the line of symmetry. There are two MCT generated analytical envelops, non-catastrophic ("initial") damage and catastrophic (structural or "final") failure. Because the failure state of each constituent is examined at every point in the load history, non-catastrophic laminate damage, usually in the form of failed matrix, can be simulated and its propagation tracked. Final failure is determined analytically when element displacements in a load increment become very large compared to previous increments.

Considering the results shown in Fig. 5, there are several observations worthy of discussion. The first is the reasonable agreement in quadrants II, III, and IV between the experimental data and MCT predictions with, in general, MCT providing a slightly conservative estimate of laminate failure strength. The only exception to this general trend occurs with the difficult load ratio of −1/−1. While it was not observed in the present study, this load ratio is particularly difficult to execute experimentally due to the presence of buckling. Further, MCT does not currently account for either macro- (specimen) or micro- (fiber) buckling effects on laminate structural response. Note also that MCT initial and final failure envelopes, for the most part, coincide in these three quadrants. Notwithstanding the −1/−1 load condition, the trend of the MCT predictions being slightly conservative to the experimental data is highly desirable scenario from a design perspective, as it equates to a slightly conservative analysis tool.

The largest discrepancy between MCT predictions and experimental data occurs in the tension/tension quadrant. A precise explanation for this discrepancy is unknown,

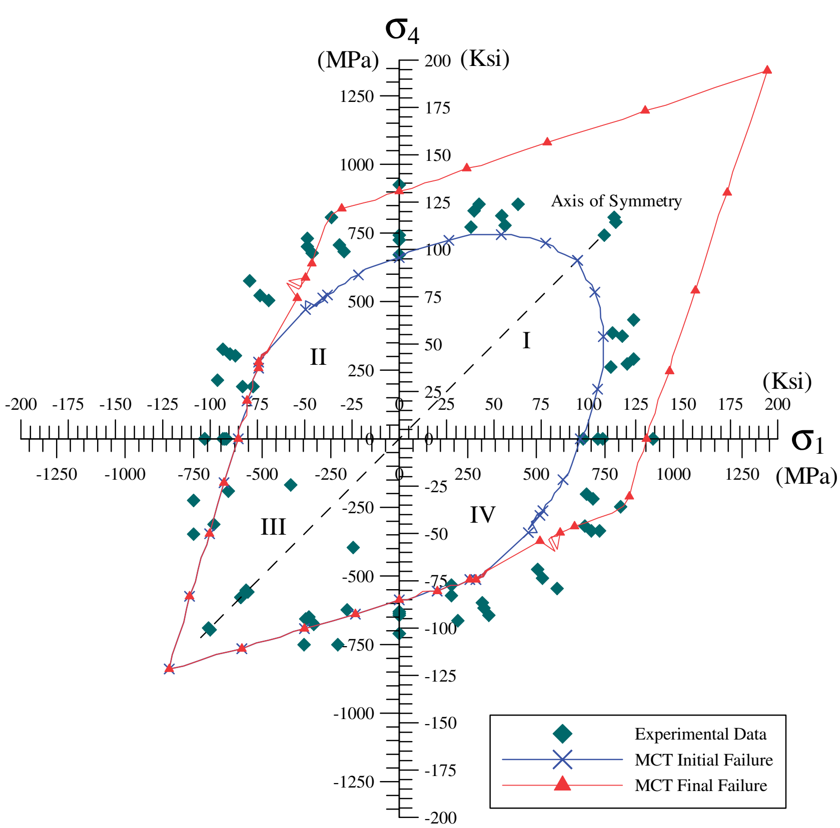

Fig. 5. Experimental and analytical biaxial failure envelopes for an IM7/977-2 quasi-isotropic laminate.

but the authors will attempt to apply experimental and analytical insight to explore potential reasons. MCT predicts simultaneous matrix failure in all eight lamina, non-catastrophic laminate damage, at approximately 50% of the final load. With the main load bearing constituent (fibers) still intact, the MCT simulation continues loading the laminate until the fibers rupture at their tensile strength value. In a single element simulation, there is an implicit assumption of continuous and undamaged fibers. Localized stress concentrations due to individual fibers breaking within the prepreg fiber bundles (tows) along with the associated load transfer, via the matrix shear, from one fiber to another to maintain internal–external force equilibrium is not captured. It is possible that the experimental data generated in quadrant I underestimate the biaxial strength of this material due to unavoidable stress concentrations in the experimental specimen. Although considerable effort was exerted while designing the current thickness-tapered specimens to minimize stress concentrations at the intersection of two adjacent loading arms, they cannot be totally eliminated. Volume averaging stress values close to and far away from such concentrations would represent a conservative determination of the true biaxial laminate strength but would bring the correlation of experimental and numerical into closer agreement. The effect of discontinuous fibers and the associated matrix interplay is not a factor in quadrant III because of high matrix compression strength. Polymer resins have approximately twice the strength in compression as in tension [15] which is reflected in the transverse tensile and compression strengths of lamina. Hence, matrix failure is delayed, relative to an absolute measure of strain, which allows it to continue its load transferring function.

A related concern with the determination of the biaxial strengths involve the use of the bypass correction factor. Because a direct measurement of the biaxial strength of composite laminates cannot be made using thickness-tapered cruciform specimens, proper application of the BCF is critical to establishing accurate results. In the present study, concerns relating to BCF calculation were raised in two primary areas. First is the validity of the specimen strain data recorded during testing. On several occasions, strain generated from uniaxial foil strain gages appeared to drift in excess of acceptable limits and exhibited inconsistent calibration feedback. These anomalies prevent the authors from definitively establishing an accurate BCF. As previously mentioned, unique bypass correction factors were developed for compressive or tensile loading, which could contribute the experimental–analytical discrepancy in quadrant I. However, the authors do not attribute the entire difference between the experimental and numerical results to the potential errors in the BCF.

Similar to the experimental procedures described in this paper, MCT analysis, at the constituent level, requires input data that cannot be easily measured. The orthotropic response of both the fiber and matrix materials is not readily available or even experimentally determinant, and therefore must be assembled or inferred from separate data sets. This situation, while undesirable, can be and has been carefully addressed using continuum theory to generate self-consistent material properties for both the fiber and matrix. However, this process does not guarantee absolute accuracy of the input material properties. For the present study, the primary concern identified after the input data sets were generated for both IM7 fiber and 977-2 resin systems, was the difference between the tensile and compressive fiber strength values. For example, in the present study, composite test data gathered from several open literature sources and using MCT analyses to "back-out" fiber strengths, the ratio of fiber tensile to compressive strength was found to be 1.72. Previous analysis performed by the current authors using similar AS4 carbon fibers found that ratio to be 0.67. This uncertainty alone could have a significant affect on the MCT predicted failure strengths in the present study and could possibly explain why better correlation was achieved in quadrants II–IV than in quadrant I.

Perhaps the most significant aspect of the results presented in Fig. 5 involve the degree of biaxial strengthening demonstrated in quadrant I. While the MCT analysis predicts a ratio of uniaxial strength (1/0 biaxial test) to biaxial tension (1/1 biaxial test) of $\sim$1.4 for the present laminate configuration, the experimental results do not support a ratio this high. The experimental results demonstrate a ratio much closer to 1, bringing into question the severity of biaxial strengthening for this laminate configuration. While the authors believe the results shown in Fig. 5 represent a significant event leading to a more thorough understanding of quasi-isotropic laminates, they also acknowledge there are additional questions that must be addressed. As discussed briefly in Section 3, elliptical failure envelopes due to interaction of field variables (stress or strain) within a failure criteria are widely accepted. The majority, but not all, of the 19 failure criteria in the WWFE predicted significant strengthening in quadrants I and III for an AS4/3501-6 quasi-isotropic, $[(0_N/90_N/\pm 45_N)_M]_S$, laminate. Further, WWFE experimental biaxial results for AS4/3501-6 $[(0_N/90_N/\pm 45_N)_M]_S$, E-glass/LY556 (epoxy) $[(90_N/\pm 30_N)_M]_S$, and E-glass/MY750 (epoxy) $[(\pm 55)_N]_S$ laminates all indicated significant strengthening in quadrants 1 and III. None the less, more experimental verification of the biaxial strengthening effect is needed especially for the subject IM7/977-2 laminate because of its wide use in the aerospace industry.

5. Conclusions

The author have presented an analytical and experimental analysis of biaxial loading of a IM7 carbon fiber/977-2 epoxy matrix, quasi-isotropic, $[(0_N/90_N/\pm 45_N)_M]_S$ composite laminate. The numerical predictions were generated using classic strain decomposition technique known as multicontinuum theory and an associated constituent based, stress-interactive, quadratic failure criteria. The experimental results were generated using thickness-tapered cruciform specimens on a triaxial material test facility located at the Air Force Research Laboratory at Kirkland Air Force Base. Correlation between experimentally and analytically generated results was good in the compression regimes of in-plane normal–normal stress space. In the tension regimes, the experimental final (catastrophic) failure more closely correlated with the analytical prediction of initial (non-catastrophic) failure than the analytical final failure prediction. The authors cite several possible explanations for the discrepancy between final failure load predictions and experimentally achieved values chief of which is stress concentrations due to discontinuous fiber reinforcement and low matrix tensile strength. The authors presented several aspects of the current procedures that should be reconsidered in future efforts to generate more accurate results.

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